

Steerable Percussion Air Drilling System

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Introduction

Conventional percussion air drilling method, on one hand, yields very high penetration rates especially in hard formations, but limits itself to straight hole drilling because it depends on the rotation of the entire drill string. On the other hand, downhole motors enable the directional control of the well bore but cannot penetrate hard rock nearly as fast because they rely on the heavy weight of the drill collars to apply a steady crushing force onto the formation as opposed to the highly concentrated percussive energy of downhole hammers [1][3][4]. The Steerable Percussion Air Drilling System is an attempt to combine the high penetration rate of percussion air drilling with the directional control techniques of conventional drilling methods. Such a system would allow *directional* drilling in *hard* rock at *high* penetration rates. The key feature of SPADS is a rotational drive mechanism that induces an indexing rotational motion onto the bit *independently* from the drill string rotation.

Objectives

The developmental effort behind the Steerable Percussion Air Drilling System was defined by the following broad objectives:

- To develop a drilling machine capable of disintegrating hard rock by *percussive* method and *independent* of the drill string rotation, i.e., a downhole hammer/motor combined together;
- To develop necessary Bottom Hole Assembly components, namely bent subs, stabilizers and a modeling software to enable the prediction and control of the direction of the well bore;

- To investigate and accommodate telemetry tools which are *not* dependent on the mud column as the data transmitting medium. The above three sections make up a complete system referred to as the Steerable Percussion Air Drilling System.

Since October 1992, the development of SPADS was jointly funded by Smith International, Inc. and the U.S. Department of Energy. The project was divided into two phases. Phase I of this project titled Steerable Percussion Air Drilling System project involved the development of a steerable hammer for the $7\frac{1}{8}$ ", $8\frac{1}{2}$ " or $8\frac{3}{4}$ " hole sizes. The ongoing Phase II of this project is called Slim Hole Directional Drilling System, and seeks to expand the envelope of SPADS to slim hole, $4\frac{1}{2}$ ", and coiled tubing applications.

The specific objectives of each phase were:

- PHASE I: To develop, field test, and tool harden an approximately $6\frac{3}{4}$ " diameter steerable percussion air drilling system capable of controlling the borehole in the desired direction. This system will consist of a self-rotating hammer, a diamond enhanced bit, bend sub, and accommodations for surveying tools such as single shot, wireline steering tool or EM MWD.
- PHASE II: Using the information and knowledge acquired in Phase I, develop, field test, and tool harden a slim hole hammer approximately $3\frac{3}{4}$ " diameter capable of operating on both drill pipe and coiled tubing. This system will similarly consist of a self rotating directional hammer, a diamond enhanced bit, a bend sub, an orienting sub, and directional surveying or wireline steering tools.

Design Approach

SPADS is similar to conventional downhole hammers in many ways and is yet unique because of its rotational bit-drive mechanism. In percussion drilling, two simultaneous actions are necessary viz., the linear reciprocating motion of the piston to generate percussive energy, and the rotational motion of the bit to position the cutters onto new areas after each impact. In conventional hammer operation, the latter is achieved through the rotation of the entire drill string. Field experience has shown that a rotational speed of 20 rpm for an impacting cycle rate of 1600 beats per minute is adequate. This translates to an angular displacement of $4\frac{1}{2}^\circ$ per impact [1][2].

SPADS incorporates a unique rotational mechanism to achieve this desired rotation of $4\text{--}5^\circ$ between impacts. The kinetic energy of the reciprocating piston is tapped into to provide the energy required to rotate the bit. The mechanism consists of a set of helical grooves on the outer surface of the piston that are keyed to the inner race of a clutch assembly. The clutch permits the inner race to rotate during one traversing direction (upstroke) but locks the race from turning during downstroke and forces the piston to turn. As the piston is keyed to the bit it induces its rotation onto the bit. The resulting motion of the bit is an intermittent indexing type rotation.

Project Specifications

PHASE I

The design and fabrication included the following:

1. Rotational Hammers:
Hammer OD: $6\frac{3}{4}$ " to $6\frac{7}{8}$ "
Hammer Length: 5 to 7 feet
Rotational Speed: 20 to 30 RPM
Output Torque: 1,000 ft-lb. maximum.
2. Percussion Bits: Diamond Enhanced bits for $7\frac{7}{8}$ ", $8\frac{1}{2}$ ", or $8\frac{3}{4}$ " hole sizes.
3. Bend Subs: Fixed or adjustable angle bend subs, from 0.5° - 3° .
4. Stabilizers: Near-bit and other stabilizers as required in the bottom hole assemblies.

The field testing plan consisted of:

1. Straight Hole testing: To harden the capability of SPADS to drill through hard rock independently from the drill string rotation.
2. Directional Hole testing: To conduct three shallow directional field tests to evaluate build rates as a function of bend angles and placement of stabilizers, effects of side loads and reactive torque, and system reliability and mean time between failures.
3. System Field Testing: To conduct up to three high angle or horizontal field tests to prove the system capability for commercialization.

In addition, the contract also calls for the evaluation of Geoscience Electronics Corporation's (GEC) electromagnetic MWD tool as a means to telemeter directional data.

PHASE II

The design and fabrication will include the following:

1. Rotational Hammers:
Hammer OD: $3\frac{3}{4}$ "
Hammer Length: 5 to 7 feet
Rotational Speed: 20 to 30 RPM
Output Torque: 500 ft-lb. maximum.
2. Percussion Bits: Diamond Enhanced bits, as required.
3. Bend Subs: Fixed or adjustable angle bend subs, as required.
4. Stabilizers: Near-bit and other stabilizers as required in the bottom hole assemblies.

The field testing plan shall consist of:

1. Straight Hole testing: Five to seven tests to harden the capability of SPADS to drill through hard rock independently from the drill string rotation.
2. Directional Hole testing: Three to five shallow directional field tests to evaluate build rates as a function of bend angles and placement of stabilizers, effect of side loads and reactive torque, and system reliability and mean time between failures.
3. System Field Testing: Three to five high angle or horizontal field tests to prove the capability of the system for commercialization.

Results

1. LAB TESTING

An in-house testing facility for SPADS was designed and built to monitor the effect of different design parameters on hammer performance. The test facility is equipped with a flow loop, a data acquisition system, and associated instrumentation to measure different parameters that will indicate the hammer performance. During the testing, the following parameters were monitored: impact frequency, impact velocity, pressure cycle in upper and lower chambers, and bit rotation.

As a result of this testing, the performance of SPADS was significantly improved by

- Optimally sizing the upper and lower chambers, and controlling charging and discharging cycles for air *to maximize the impact energy and the operating frequency* i.e., rate of energy transfer to the bit.
- Optimally distributing the kinetic energy of the piston between linear and rotational motion, *to ensure adequate bit rotation under extreme conditions of torque.*

2. FIELD TESTING

A number of field tests were conducted in Phase I of this project mainly in 7 $\frac{7}{8}$ " and 8 $\frac{1}{2}$ " holes. The first set of tests were conducted in straight hole to demonstrate the ability of the system to drill straight through hard rock independent of the drill string rotation at good penetration rates. During 1994-1995 a total of seven straight hole field tests were conducted in West Virginia and West Texas during which the hammer was hardened and has demonstrated its ability to drill approximately 1,000 ft without failure.

While the drilling machine proved its ability to drill at a penetration rate (ROP) exceeding 90 feet per hour without drill string rotation, it also showed its sensitivity to excessive weight on bit (WOB). Occasional stalling of the piston was seen during these tests. Additional lab testing was conducted to gain better understanding about the effect of different operational variables on the magnitude of the torque required to rotate the bit. A torque sub was fabricated to monitor this torque real time during drilling.

Among the different variables such as WOB, side loads, and different formations, the lab testing conclusively indicated that there is an optimum range of WOB corresponding to every operating pressure at which torque is reasonably low. An increase in WOB above this optimum is accompanied by an increase in torque and a corresponding decrease in ROP. Clearly, as torque increases, more energy must be imparted towards rotational motion thereby reducing impact velocity and ROP. This torque must be kept reasonably low to ensure continuous cycling of the piston.

A significant improvement in performance was observed when drilling with a pull down rig, which allows WOB to be accurately controlled. A surface WOB control means such as a pull down rig is most desirable but may not always be available in the field and would probably prove inadequate in presence of drag during directional and horizontal drilling. A downhole sub, called as Constant-WOB sub, was designed to maintain a constant hold down force necessary for uninterrupted hammer operation, while keeping the torque to a minimum. Since the hold down

force applied by this sub is proportional to the operating pressure, optimum WOB is automatically maintained over a wide range of line pressures.

The directional field testing phase for this project commenced in 1996. The objectives of these tests were to demonstrate the ability of the hammer to build angle and steer the direction of the well bore and to study the build rates and dogleg severities obtained with different BHAs consisting of different bend angles. During the course of four tests conducted to date, the hammer has successfully completed its primary objective by demonstrating the ability to build hole angle as well as change hole direction. The magnitude of build rates and dogleg severities as a function of the bend angle is shown in Figure 1 and compared to those obtained with a conventional PDM motor [5].

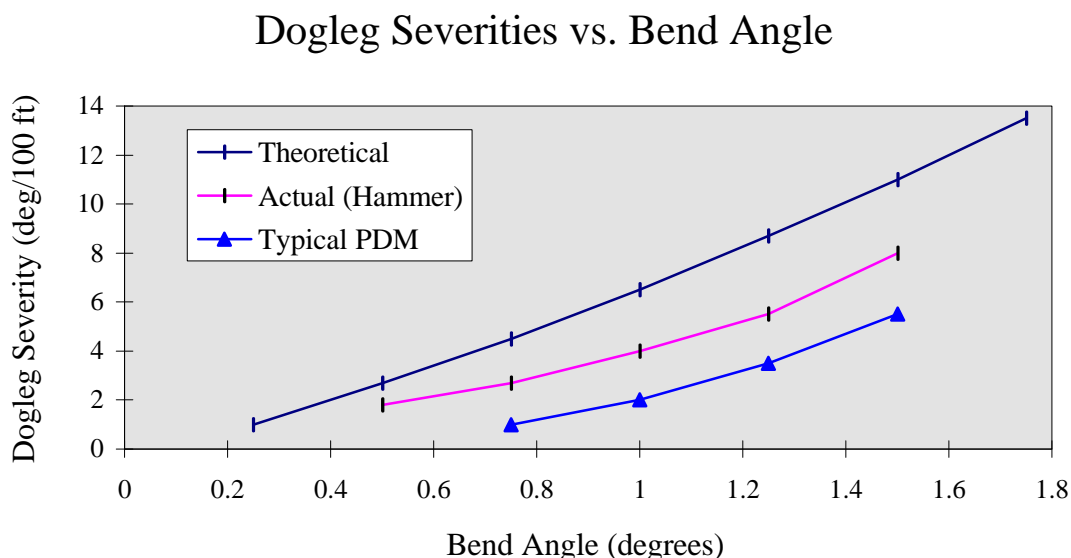


Figure 1: Build Rates with SPADS

During its build and turn sections, the hammer drilled at good penetration rates (60-120 ft/hr) comparable to a straight hole ROP with a conventional air hammer. The formations ranged from soft shale to hard limestone and granite (with compressive strength as high as 22,000 psi). Build rates with SPADS were generally greater than conventional downhole motors for similar bottom hole assemblies. The reactive torque during directional field testing was low; in the range of 500-1,000 ft-lb. More importantly, this torque is cyclic in nature, not constant as observed in downhole motors. As a result, the tool face stays mostly constant, allowing easy control of the hole azimuth.

The typical BHA consisted of a diamond enhanced hammer bit, steerable hammer, bend subs (bend angles ranging from 0.5-1.5°), constant WOB sub, mule shoe sub, and nonmagnetic collars. Single shot equipment was used during most of the tests to survey and orient the tool face.

The directional field tests conducted to date have shown the feasibility of drilling “Pad” type directional drilling applications, so as to eliminate expensive location costs [6]. SPADS is

currently being commercialized for directional sidetracks, build sections, and short correction runs for directional wells in hole sizes ranging from 7 $\frac{7}{8}$ "-8 $\frac{3}{4}$ ".

Future Activities

PHASE I

The additional side load encountered in directional drilling has reduced the life of different components to a few hundred feet. Engineering efforts are focused on further hardening the tool to at least a few thousand feet for directional and horizontal drilling applications. It is our goal to complete Phase I by conducting the system field tests in highly deviated or horizontal holes in 1997.

PHASE II

The preliminary design of the 3 $\frac{3}{4}$ " O.D. hammer has been completed. Fabrication of three prototypes is currently underway. The schedule of Phase II calls for straight hole testing of this hammer with coiled tubing in the second quarter of this year. A downhole sub which allows the tool face to be oriented in coiled tubing applications will be designed and fabricated for the directional and horizontal field tests to be conducted in 1998. The slim hole directional drilling system will open doors to new directional wells as well as deepening existing wells.

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